SUBSTITUTE SPECIFICATION

SYSTEM AND METHOD FOR THREE-DIMENSIONAL
RECONSTRUCTION OF AN ARTERY

FIELD OF THE INVENTION

The present invention relates to medical devices, and more specifically to such devices for use in angiography.

BACKGROUND OF THE INVENTION

5   Stenosis of an artery refers to narrowing of the artery lumen due to plaque formation on the interior wall of the artery. The severity of the stenosis is the fraction of the cross-sectional area of the lumen that is occluded by plaque. Since narrowing is often asymmetrical about the axis of the artery, in order to assess the severity of a stenosis, it is necessary to obtain at least two, and preferably more,

10   images perpendicular to the artery axis from orthogonal perspectives.

    In angiography, the arterial lumen is filled with a radio-opaque substance and X-ray images of the arterial tree are obtained from different perspectives. Selection of these perspectives is partly arbitrary and partly a process of trial and error once a stenosis has been observed. However, the overall number of images

15   that can be obtained is limited by time, safety and cost. Usually four to seven projections for the left coronary arterial system and two to four for the right coronary artery are obtained. The operator assesses the severity of the stenosis either on the basis of visual examination of the images or by computer analysis of a single image. Since these projections are in general not perpendicular to the arterial

20   axis, estimation of stenosis severity and its length from these images is usually not accurate.

SUMMARY OF THE INVENTION

It is therefore an object of the invention to provide a more accurate process and system for computer reconstruction of an artery from discrete images of the artery.

5   Such an objective is realized in accordance with a first aspect of the invention by a system comprising means for obtaining two-dimensional angiographic images of arteries, and a microprocessor for processing the images. The images may be obtained, for example, by X-ray angiography or by ultrasound.

In accordance with a second aspect of the invention, there is provided a 10   process for obtaining two or more angiographic images of an arterial tree. The images preferably include two images taken from perpendicular perspectives. In the case of the coronary arterial tree, all images are preferably obtained when the heart is in the same state, for example, diastole. A three dimensional (3D) reconstruction of the arterial tree is generated by the microprocessor from the images by methods 15   known in the art. Methods of generating a 3D reconstruction of an arterial tree from discrete images can be found, for example, in anyone of the following references all of which are included herein in their entirety by reference: Faugeras, O.D., Mass. Inst. Tech. 1993; Garreau, *et al.*, IEEE Trans Med Imag 10(2):122-131; Grosskopf, S, Dissertation, Technical University of Berlin, 1994; and Hildebrand 20   and Grosskopf, in Proc. Comp. Assisted Radiology CAR 95 conference, Berlin Springer, pp 201-207, 1995. The arterial tree may be, for example, the coronary arterial tree, the renal arterial tree, the pulmonary arterial tree, the cerebral arterial tree, or the hepatic arterial tree.

The 3D reconstructed arterial tree may be represented on a display screen 25   using pseudo 3D effects such as directional lighting and shading. In a preferred embodiment, the reconstructed tree is presented as a stereoscopic pair of images to be viewed by the operator using a stereoscopic viewer. The reconstruction may be manipulated on the screen by the operator, allowing him, for example, to zoom in on a specific region or to rotate the reconstructed artery on the screen to obtain a 30   desired perspective.

An artery, for example, a stenotic or aneurotic artery present in any of the obtained angiographic images may be detected by analysis of the images by the microprocessor or by visual examination of the images by the operator. The microprocessor determines the orientation of the axis of the artery in the 3D
5   reconstruction of the arterial tree. The microprocessor then calculates two or more perspectives of the artery perpendicular to the arterial axis. Preferably, two orthogonal perspectives are determined. If images of the selected artery have not already been obtained approximately from the calculated perspectives, the operator obtains angiographic images of the artery from these perspectives and the
10 microprocessor then constructs a 3D reconstruction of the artery from the angiographic images by methods known in the art. The invention thus allows an operator to obtain images of the artery from orthogonal perspectives more rapidly than is possible by prior art methods of trial and error. This allows a smaller radio-opaque dosage to the patient and a reduced exposure of the patient and the operator
15 to X-rays.

The microprocessor may apply metrological tools to the reconstructed artery. In the case of a stenotic artery, the microprocessor may provide accurate quantitative assessment of the extent and length of the stenosis. The severity of a stenosis may be described quantitatively, for example, by the fraction of the arterial
20 lumen occupied by plaque.

The 3D reconstructed artery may be represented on a display screen using pseudo 3D effects such as directional lighting and shading. In a preferred embodiment, the reconstructed artery is presented as a stereoscopic pair of images to be viewed by the operator using a stereoscopic viewer. The reconstruction may
25 be presented to the operator embedded in the 3D reconstruction of the entire arterial tree. The reconstruction may be manipulated on the screen by the operator, allowing him, for example, to zoom in on a specific region or to rotate the reconstructed artery on the screen to obtain a desired perspective of the stenosis including a perspective showing maximal narrowing or a cross section of the artery.

Thus, in its first aspect the invention provides a system for imaging an artery contained in an arterial tree, the artery having an axis, the system comprising:

    a   a microprocessor configured to

        aa   generate a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

        ab   determine an orientation of the axis of the artery in the arterial tree;

        ac   determine from the three-dimensional reconstruction of the arterial tree at least one perspective of the artery perpendicular to the axis of the artery; and

        ad   generate a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective.

In its second aspect, the invention provides a method for imaging an artery contained in an arterial tree, the artery having an axis, the method comprising the steps of:

    a   generating a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

    b   determining an orientation of the axis of the artery in the arterial tree;

    c   determining from the three-dimensional reconstruction of the arterial tree at least one perspective of the artery perpendicular to the axis of the artery; and

    d   generating a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective.

In its third aspect, the invention provides a method for diagnosing stenosis in an arterial tree in an individual, the method comprising the steps of:

      a   generating a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

      b   detecting in the three-dimensional reconstruction of the arterial tree a stenotic artery, the stenotic artery having an axis;

      c   determining an orientation of the axis of the stenotic artery;

      d   determining from the three-dimensional reconstruction of the arterial tree at least one perspective of the stenotic artery perpendicular to the axis of the artery;

      e   generating a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective; and

      f   analyzing the three-dimensional reconstruction of the artery.

In its fourth aspect, the invention provides a program storage device readable by machine, tangibly embodying a program of instructions executable by the machine to perform method steps for imaging an artery contained in an arterial tree, the artery having an axis, said method steps comprising:

      a   generating a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

      b   determining an orientation of the axis of the artery in the arterial tree;

      c   determining from the three-dimensional reconstruction of the arterial tree at least one perspective of the artery perpendicular to the axis of the artery; and

      d   generating a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective.

In its fifth aspect, the invention provides a computer program product comprising a computer useable medium having computer readable program code

embodied therein for imaging an artery contained in an arterial tree, the artery having an axis, the computer program product comprising

     a   computer readable program code for causing the computer to generate a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

     b computer readable program code for causing the computer to determining an orientation of the axis of the artery in the arterial tree;

     c computer readable program code for causing the computer to determine from the three-dimensional reconstruction of the arterial tree at least one perspective of the artery perpendicular to the axis of the artery; and

     d computer readable program code for causing the computer to generate a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective.

In its sixth aspect, the invention provides a program storage device readable by machine, tangibly embodying a program of instructions executable by the machine to perform method steps for diagnosing stenosis in an arterial tree in an individual, said method steps comprising:

     a   generating a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

     b   detecting in the three-dimensional reconstruction of the arterial tree a stenotic artery, the stenotic artery having an axis;

     c   determining an orientation of the axis of the stenotic artery;

     d   determining from the three-dimensional reconstruction of the arterial tree at least one perspective of the stenotic artery perpendicular to the axis of the artery;

     e   generating a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective; and

     f   analyzing the three-dimensional reconstruction of the artery.

In its seventh aspect, the invention provides a computer program product comprising a computer useable medium having computer readable program code embodied therein for diagnosing stenosis in an arterial tree in an individual the computer program product comprising:

5   **a** computer readable program code for causing the computer to generate a three-dimensional reconstruction of the arterial tree from two or more angiographic images of the arterial tree obtained from different perspectives;

         b computer readable program code for causing the computer to detect in the three-dimensional reconstruction of the arterial tree a stenotic artery, the

10   stenotic artery having an axis;

         c computer readable program code for causing the computer to determine an orientation of the axis of the stenotic artery;

         d computer readable program code for causing the computer to determe from the three-dimensional reconstruction of the arterial tree at least one

15   perspective of the stenotic artery perpendicular to the axis of the artery;

         e computer readable program code for causing the computer to generate a three dimensional reconstruction of the artery from angiographic images obtained essentially from the determined at least one perspective; and

         f computer readable program code for causing the computer to analyze

20   the three-dimensional reconstruction of the artery.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

25   **Fig. 1** shows a cross-sectional view and two projections of a stenotic artery;

         Fig. 2 is block diagram showing an embodiment of the system of the invention according to one embodiment of the invention; and

         Fig. 3 is a flow chart diagram of the process of constructing a three-dimensional reconstruction of a stenotic artery.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Referring first to Fig. 1, a cross section **100** of a stenotic artery is shown. The artery has a circular lumen that is partially occluded by plaque **105**. In angiography, the unoccluded portion of the lumen **110**, (indicated in Fig. 1 by

5 cross-hatching) is filled with a radio-opaque substance. **115a** and **115b** are two longitudinal projections of the radio-opacity of the artery as would be obtained in angiography. The projections **115a** and **115b** are from orthogonal perspectives as indicated by the broken lines **120a** and **120b**. In the projection **115a** the stenosis appears to be non-critical. The projection **115b**, on the other hand, shows maximal

10 narrowing of the arterial lumen indicating that the stenosis is in fact critical.

In Fig. 2, a block diagram of a preferred embodiment of the system of the invention is shown. An X-ray source **200** and an X-ray detector **205** are used to obtain angiographic images of an individual **210**. An X-ray beam **212** is produced by the X-ray source **200** and is detected by the detector **205** after having passed

15 through the body of the individual **210**. The analog signal **215** produced by the detector **205** is converted into a digital signal **225** by analog-to-digital converter **220**. The digital signal **225** is inputted into a microprocessor **230** and stored in a memory **240**. An analog ECG signal **270** may also be simultaneously obtained from the individual **210**. The analog ECG signal **270** is converted into a digital signal

20 **280** by analog-to-digital converter **275** and the digital ECG signal **280** is inputted to the microprocessor **230** and stored in the memory **240**. The detector signal **225** and the ECG signal **280** are synchronized by the microprocessor **230**. An operator input **250,** that may be, for example, a key board or a computer mouse, is used to allow an operator to input instructions to the microprocessor **230**. A display **255** is used to

25 display images either in real-time or images called up from the memory **240**.

The orientation of the X-ray beam **212** and the plane **260** of the individual's body may be selected by the operator in order to produce an image of an arterial tree of the individual, for example, the coronary artery tree, from a desired perspective. The operator inputs the desired perspective into the microprocessor

230 by means of operator input 250. The microprocessor 230 then brings the X-ray source 200 and the detector 205 into the required orientation by activating a mechanism (not shown) that moves the X-ray source and the detector into the desired orientation relative to the individual's body, as is known in the art.

5   The microprocessor 230 is programmed to generate a 3D reconstruction of the arterial tree based upon the obtained images. The 3D reconstruction of the arterial tree may be represented on display 255 using pseudo 3D effects such as directional lighting and shading. In a preferred embodiment, the reconstructed tree is presented as a stereoscopic pair of images on display 255 to be viewed by the

10   operator using a stereoscopic viewer. The 3D reconstruction of the arterial tree may be manipulated on the display 255 by the operator by means of operator input 250, allowing him, for example, to zoom in on a specific region, or to rotate the reconstruction on the display to obtain a desired perspective.

An artery of interest, for example, a stenotic artery, in an image or in the 3D

15   reconstructed tree is selected by the operator or detected by the microprocessor, for example, by gray level analysis as is known in the art. For example, an image or the reconstructed tree may be displayed on the display 255, and an artery selected by the operator by means of input 250. The microprocessor determines from the 3D reconstruction of the arterial tree the angular orientation of the selected artery. The

20   microprocessor then calculates two or more perspectives perpendicular to the axis of the selected artery. The perspectives preferably include two orthogonal perspectives. If images of the selected artery have not already been obtained approximately from the calculated perspectives, the operator obtains such images. The microprocessor 230 is programmed to reconstruct a 3D image of the selected

25   artery based upon these images. The 3D reconstruction of the artery may be represented on display 255 using pseudo 3D effects such as directional lighting and shading. In a preferred embodiment, the reconstruction is presented as a stereoscopic pair of images on display 255 to be viewed by the operator using a stereoscopic viewer. The reconstruction of the artery may be presented to the

30   operator embedded in the 3D reconstruction of the entire arterial tree.

The 3D reconstruction of the artery may be manipulated on the display **255** by the operator by means of operator input **250,** allowing him, for example, to zoom in on a specific region or to rotate the reconstruction on the display to obtain a desired perspective, including an optimal perspective or a cross-section.

5   The microprocessor may optionally be programmed to determine quantitative and qualitative parameters of a stenosis based upon the 3D reconstruction. Such parameters may include, for example, the length and severity of a stenosis.

Referring now to Fig. 3, a flow chart is shown describing a preferred 10   embodiment of the process of the invention. At step **310** the operator obtains at least two angiographic images of an arterial tree of the individual **210** from different, preferably perpendicular, perspectives. The images are displayed on the display **255** in step **315**, and a 3D reconstruction of the arterial tree is generated from the obtained images **318**. The 3D reconstruction may optionally be displayed 15   on the display **255**. The obtained angiographic images or the 3D reconstructed tree is examined for arteries of interest, for example, stenotic arteries. The examination may be performed either automatically by the microprocessor **230** or by visual examination by the operator (step **320**). If no artery of interest is detected in any of the images or in the 3D reconstructed tree the operator decides whether additional 20   images are to be obtained from a new perspective (step **330**). If at step **330** the operator decides not to obtain additional images, the process is terminated. If, at step **330** the operator decides to obtain an additional image, a perspective is selected and the operator inputs the perspective into the microprocessor **230**, and the process then returns to step **315**. If in step **320** one or more arteries of interest 25   are observed, an artery of interest is selected in step **340.** In step **345** the microprocessor calculates two or more perspectives perpendicular to the axis of the selected artery (step **348**). The perspectives preferably include two orthogonal perspectives. If images of the selected artery have not already been obtained approximately from the calculated perspectives, the operator obtains such images 30   (step **348**). In step **350,** the microprocessor updates the 3D reconstruction of the

artery. The reconstructed artery is displayed on the display **255** in step **355** together with parameters describing the artery. For example, for a stenotic artery, the parameters may include the severity and length of the stenosis. The reconstructed artery may be presented to the operator embedded in the 3D reconstruction of the entire arterial tree. The operator may change the display using input **250**, for example, by rotating the reconstructed artery on the display **255** so as to change the scale of the reconstruction of the artery or view the reconstruction from a desired perspective, including an optimal perspective or a cross-section. The operator then decides in step **360** whether he wishes to obtain a 3D reconstruction of another artery of interest in the arterial tree. If so, the process returns to step **340.** If not, additional images are desired, the process terminates.

It will also be understood that the system according to the invention may be a suitably programmed computer. Likewise, the invention contemplates a computer program being readable by a computer for executing the method of the invention. The invention further contemplates a machine-readable memory tangibly embodying a program of instructions executable by the machine for executing the method of the invention.

In the method claims that follow, alphabetic characters used to designate claim steps are provided for convenience only and do not imply any particular order of performing the steps.